

Processing and Interpretation of Permanent Downhole Monitoring Data

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Abstract

In recent years, permanent down-hole gauge (PDG) has been widely installed in oilfields around the world to monitor the reservoir and well conditions in real time. Continuous monitoring of pressure enables engineers to observe ongoing changes in the well and makes operating adjustments accordingly to enhance oil and gas recovery. Transient pressure monitored by PDG are characterized with long term and high volume data which are inherently noisy, full of variable-rate superposition and multi-well interference effects. These effects make the monitoring pressure trends decline or rise and then obscure or distort the traditional flow behavior, which makes the following analysis difficult. This paper has presented a systematic methodology that tackled the issues related to the permanent down-hole monitoring data, utilizing both the wavelet transform and multi-well deconvolution techniques. With this developed method, the outlier information in PDG data can be extracted. The variable-rate superposition and inter-well interference effects can be removed at the same time. Moreover, hundreds of pressure events i.e. bulidups and drawdowns can be detected and reconstructed to reflect reservoir properties and connectivity across the reservoir. The whole workflow for processing and interpretation of permanent down-hole monitoring data is proposed in this paper. Field case study is performed to demonstrate these procedures. The study results prove that the developed method works well in processing and interpretation of long-term permanent down-hole monitoring data.

Keywords

Permanent Down-Hole Gauge; Reservoir Monitoring; Wavelet Transform; Deconvolution Transform; Data Processing

Introduction

Permanent down-hole gauges (PDG) are metering devices installed down-hole to monitor the well and reservoir conditions in real time. Technology has evolved over more than 40 years since the first installation (Chorneyko, D.M., et al., 2006). Installation of these gauges has been an increasingly common industry practice worldwide because of the improved reliability and the value of information that the gauges

provide. PDG components include gauges, housing, cable, connections, and acquisition systems, as shown in Fig.1. Permanent monitoring systems measure and record well performance and reservoir behavior from sensors which are placed downhole during the completion. These measurements give engineers information essential to dynamically manage hydrocarbon assets, allowing them to optimize production techniques, diagnose problems, refine field development and adjust reservoir models. Sensors are placed downhole with the completion string close to the heart of the reservoir. Modern communications provide direct access to sensor measurements from anywhere in the world. Reservoir and well behaviors may now be monitored easily in real time, 24 hours a day, day after day, throughout the lifetime of the reservoir. Engineers can catch performance daily, examine responses to changes in production or secondary recovery processes and also have a record of events to help diagnose problems and monitors in a power plant's control room (Athichanagorn, Suwat, et al, 1999; Frota, H.M. and Destro, W., 2006) .

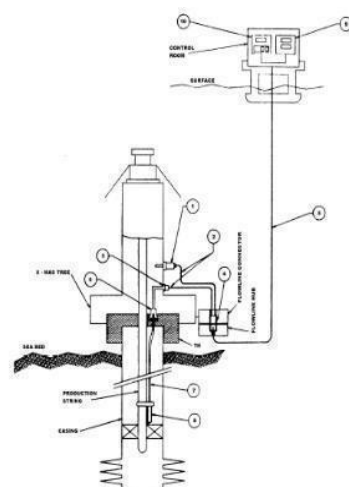


FIG.1 PERMANENT DOWNHOLE GAUGE

Data from permanent down-hole gauges can be examined and collected almost as soon as they are acquired at the down-hole of the well. A wide range of

application of permanent downhole gauge data has been reported in the oil and gas industry (Ouyang, L.B. and Kikani, J., 2002; McCracken, M. and Chorneyko, D., 2006; Tibold, M.P., et al., 2000; Queipo, N.V., et al., 2002; Gringarten, A.C., et al., 2003). These applications include: reduction on ambiguity and uncertainties in the interpretation; detection of the changes in reservoir properties; monitoring of skin, permeability, pressure drawdown over time; monitoring of hydraulic fracturing operations; pump inlet and outlet pressures for pumping wells; evaluation on the performance of well completion, simulation or workover; identification of reservoir connectivity; evaluation on operational efficiency; reduction on the flowback time of new wells; and assistance in reservoir simulation and history matching.

In practice, there are issues associated with the data that these gauges collect. Large amounts of data are gathered continuously at intervals down to one second over several years, as shown in Fig.2. This data contains more information about the reservoir parameters changing during short and long time intervals than data from traditional pressure transient tests which last for relatively small durations. In this situation, more information will be hidden in this long-term PDG pressure record than just a collection of drawdowns and buildups, which makes the interpretation of PDG data a new challenge.

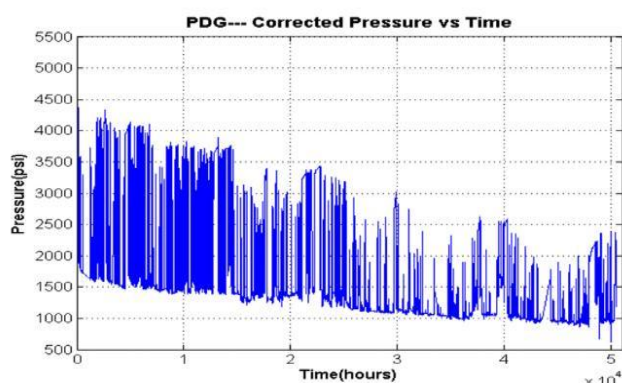


FIG. 2 PERMANENT DOWNHOLE GAUGE DATA

Besides the characteristic of long term and large volume, there are several issues related to this kind of PDG pressure data, such as the data are inherently noisy because they are obtained under uncontrolled conditions. Moreover, it involves two key effects in the transient pressure data from permanent down-hole gauges, namely, multi-rate superposition and multi-well interference effects. Multi-well interference effect, a very common in PDG pressure data in oilfield practice (Britt, L.K., et al., 1991; Erwin, M.D., et al.,

2002), makes the measured pressure trends decline or rise and then obscures or distorts the traditional flow behavior, which makes the following analysis difficult, i.e. the construction of the incorrect semi-log straight line or the incorrect radial flow regime on a pressure derivative log-log plot.

These issues have motivated several studies in data processing, noise reduction and new interpretation methodologies for the permanent down-hole gauge data. Xiaogang Li(2009) proposed a wavelet based data processing and interpretation procedure. Fei Wang (2010) presented a deconvolution based method for multi-rate superposition and well interference extraction. In this paper, the above two methodologies are organized and integrated into a newly released procedure for processing and interpretation of PDG data. This procedure was presented as a multiple-step methodology that tackled the different issues related to the data acquired from permanent down-hole gauges.

Workflow for Processing and Interpretation of PDG Data

The newly released workflow for permanent down-hole gauge data includes four procedures, shown in Fig.3. In collecting data, the focus is tried on the dynamic data, especially PDG pressure and production data. Then the PDG data was processed and analyzed in three different ways: wavelet-based welltesting, deconvolution-based welltesting and numerical welltesting. Finally, all the results were integrated by means of future history match. The target is to apply PDG data to improve the reservoir model.

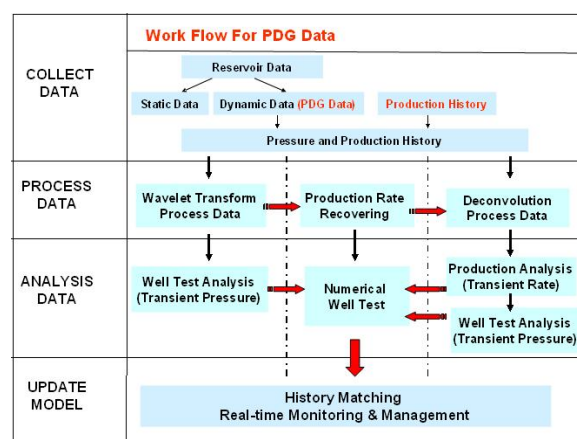


FIG. 3 WORKFLOW FOR PROCESSING AND INTERPRETATION OF PDG DATA

The workflow follows two ways and reaches the same goal. One way, shown on left side of the picture, uses

the wavelet-based welltest to analyse the data in order to get the changed parameter of reservoir property. The main drawback of this way is to handle the noise and huge amounts of data before the welltest analysis is implemented. The wavelet transform proved to be an effective approach to solve this problem just concentrates on each flow regime of the reservoir behaviour.

The other way, shown on right side of the picture, uses the whole test sequence in the welltest analysis by deconvolution processing. This approach gives much higher estimates on the test area without any flow regime or reservoir geometry limitations. Multi-rate superposition and well interference problems in PDG data can be solved in this procedure.

The result of the analytical well test gives the range which is the first guess of the reservoir parameters. Then the near well model is validated by numerical well testing. This part model is integrated with the whole reservoir model to achieve the true reservoir model. This workflow includes two main techniques i.e wavelet-based data processing and deconvolution-based data processing. The detailed methodologies are presented as follows.

PDG Data Processing Technique

The data processing technique involves two approaches i.e. wavelet and deconvolution, which prepare the PDG data for the following well test analysis. The procedure will first divide the whole PDG data into separated buildup (BU) and drawdown (DD). The wavelet transform is applied to identify the event of outlier, BU and DD in the high frequency signal. Then the separated BU and DD sequence without outlier will be deconvolved to achieve multi-rate normalization and interference extraction. The final step is to compress and smooth data in order to get the trend of derivative in the log-log plot. The data is compressed according to the variety of signal. More data points will be kept when the signal changed significantly. And the sample interval is allocated according to the log scale. The compressed signal is still noised in the log-log plot. So, further smooth data is necessary to clean derivative. Lowess and loess method will be used to smooth these data. During this processing procedure, the different issues related to the PDG data can be tackled.

Theory Background of Wavelet Transform

A wavelet, a wave-like oscillation with an amplitude

that starts at zero, and increases, and then decreases back to zero, can typically be visualized as a "brief oscillation" like one might see recorded by a seismograph or heart monitor. In mathematics, a wavelet series is a representation of a square-integrable function by a certain orthonormal series generated by a wavelet.

The integral wavelet transform is the integral transform defined as

$$[W_{\psi} f](a, b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} \psi\left(\frac{x-b}{a}\right) f(x) dx \quad (1)$$

The wavelet coefficients c_{jk} are then given by

$$c_{jk} = [W_{\psi} f](2^{-j}, k2^{-j}) \quad (2)$$

Here, $a = 2^{-j}$ is called the binary dilation or dyadic dilation, and $b = k2^{-j}$ is the binary or dyadic position.

The continuous wavelet transform (CWT) is defined as the sum over all time of the signal multiplied by scaled, shifted versions of the wavelet function ψ :

$$C(\text{scale}, \text{position}) = \int_{-\infty}^{\infty} f(t) \Psi(\text{scale}, \text{position}, t) dt \quad (3)$$

The results of the CWT are many wavelet coefficients C , which are a function of scale and position. Scaling a wavelet simply means stretching (or compressing) wavelet, shown in Fig.4.

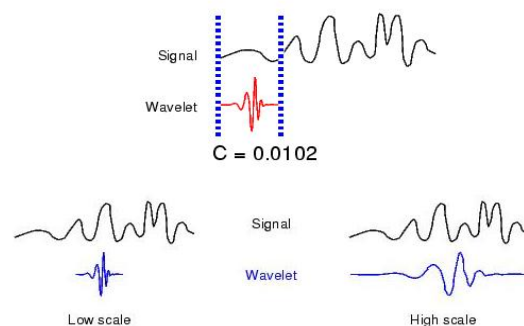


FIG. 4 DIAGRAM OF CONTINUOUS WAVELET TRANSFORM

The first discrete wavelet transform(DWT) was invented by the Hungarian mathematician Alfréd Haar. For an input represented by a list of $2n$ numbers, the Haar wavelet transform may be considered to simply pair up input values, storing the difference and passing the sum. This process is repeated recursively, pairing up the sums to provide the next scale: finally resulting in $2n - 1$ differences and one final sum.

The Haar wavelet's mother wavelet function $\psi(t)$ can be described as

$$\psi(t) = \begin{cases} 1 & 0 \leq t < 1/2, \\ -1 & 1/2 \leq t < 1, \\ 0 & \text{otherwise.} \end{cases} \quad (4)$$

Its scaling function $\phi(t)$ can be described as

$$\phi(t) = \begin{cases} 1 & 0 \leq t < 1, \\ 0 & \text{otherwise.} \end{cases} \quad (5)$$

Mathematically, the wavelet can be used to extract information from many different kinds of data, because it will resonate if the unknown signal contains information of similar frequency.

Wavelet-based PDG data Processing

Wavelet-based processing approach allows the use of long time intervals where more precise low-frequency information is desirable, and shorter regions where high-frequency information is desirable. While an advantage of using haar wavelets is for the analysis of signals with sudden transitions, just like the PDG data with outliers.

The outlier which is isolated and lies away from the rest of the PDG data can cause discontinuities in the data stream creating two consecutive singularities. For example, an outlier that lies above the trend of the data departs from the data trend, creating the first singularity. The second singularity is a result of a sudden decrease from the outlier back to the trend of the signal. This characteristic can be exploited using a singularity detection frame with wavelets. When an outlier exist, the detail signal will first change sharply in one direction, either increasing or decreasing, and then change again in the opposite direction. Therefore, the singularities created by the outliers can be detected by screening for two large magnitudes of the detail signal with opposite signs. In order to determine the outliers, a threshold is set up for the magnitude of the detail signal.

Generally, a complete record of times at which the well flow rate change is not available. Fortunately, the times at which the flow rates change can be determined by identification of sudden changes in pressure data. These changes can be viewed as singularities in the data. Therefore, the wavelet modulus maximal, which indicates the neighborhoods of singularities, can be used to determine the times at which flow rate changes, then the BU can be separated from the DD.

The procedure of wavelet method to process and

analyze PDG data has shown in Fig.5. First, the data evaluation will be applied to know the distribution of data point. Second, detection of algorithm will release the separated BU and DD without outlier. Third, individual BU and DD are compressed and denoised in order to get the high quality signal in log-log plot. At last, the signal is plotted in the log-log plot for analysis.

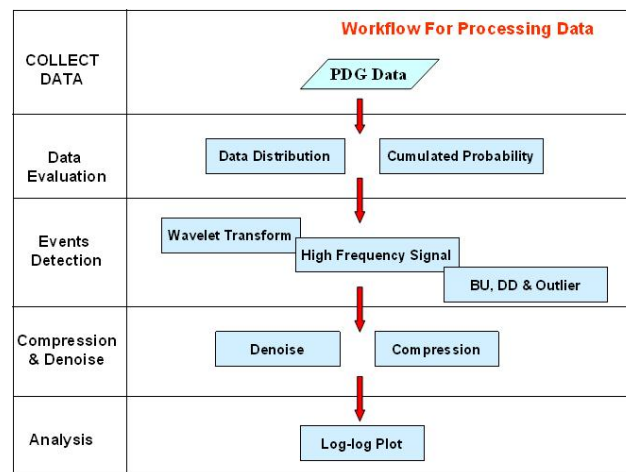


FIG.5 WAVELET-BASED PDG DATA PROCESSING

The procedure to detect event is as follows:

- Calculation on the data distribution of detail signal can help to get the first guess for threshold in identifying the event.
- This threshold is used to get all high frequency signals which include DD, BU and outlier.
- Classify these data into different group. If the group size is small, this may be the outlier. And these data values of original signal are required to check.
- if the group size is big (more than 1min), this can be considered as the begin of BU or DD. Then the original data in the both side of group need to be checked as well. This can identify the BU and DD.
- Then if the group is the beginning of BU, then check the distribution of the following data of group to identify the shut-in-BU or rate-drop-BU.

Theoretical Background of Deconvolution Transform

Hypothesis: $h(t)$ is a linear response of a system, the output is $y(t)$ and input is $x(t)$.

So $y(t)$ can be written as a convolution integral as follows:

$$y(t) = \int_{-\infty}^{\infty} h(t-\tau)x(\tau)d\tau \quad (6)$$

With given output $y(t)$ and input $x(t)$ to recover the system response $h(t)$ is so-called Deconvolution. Once the convolution integral (Eq.6) is applied to single-well problem, it turns to be Duhamel principle:

$$\Delta p(t) = p_i - p_{wf}(t) = \int_0^t q(\tau) \frac{dp_u(t-\tau)}{dt} d\tau \quad (7)$$

Where, $q(t)$ and $p_{wf}(t)$ are the measured flow rate and bottom-hole pressure. p_i is the initial pressure and p_u is the unit-rate pressure response, referred to as the impulse response of the reservoir system.

It is assumed that there are n active wells in a reservoir and these wells are in good connectivity with each other. When using $x = 1, 2, \dots, n$ to denote each of these wells, the total bottom-hole pressure drop of well x can be expressed as follows:

$$p_x(t) = p_i - \int_0^t q_x(t-\tau) \frac{dp_{uxx}(\tau)}{dt} d\tau - \sum_{y=1}^n \int_0^t q_y(t-\tau) \frac{dp_{uxy}(\tau)}{dt} d\tau \quad (8)$$

$(x \in n, y \in n, x \neq y)$

It means that the down-hole pressure drop measured in one well benefits from not only its self-production but also the production of other active wells in the same reservoir. And the relationship follows superposition principle.

In the multi-well convolution function above, p_{uxx} represents the pressure response at the down-hole of well x due to the production itself, while p_{uxy} represents the interference response, namely the pressure response at the down-hole of well x due to the unit-rate production of well y . Multi-well deconvolution is to extract the self and interference information from the total dataset.

Deconvolution-based PDG data processing

Deconvolution-based processing approach can convert a series of transient pressure, due to variable or step rate history into an equivalent unit-pressure transient rate. The interference information can be extracted as well from the total pressure response data. Namely, multi-well deconvolution removes the effects of well rate variation and of the interferences from other wells operating in the reservoir and reconstructs the characteristic pressure transient response to unit-rate

production of each active well in the reservoir. These deconvolved responses to unit-rate production reflect reservoir properties and connectivity across the reservoir. Recovery of this information early in the life of the field through integrated analysis of dynamic pressure data provides an opportunity to adjust and optimize reservoir development plans.

The procedure of multi-well deconvolution method to process and analyze PDG data has been shown in Fig.6.

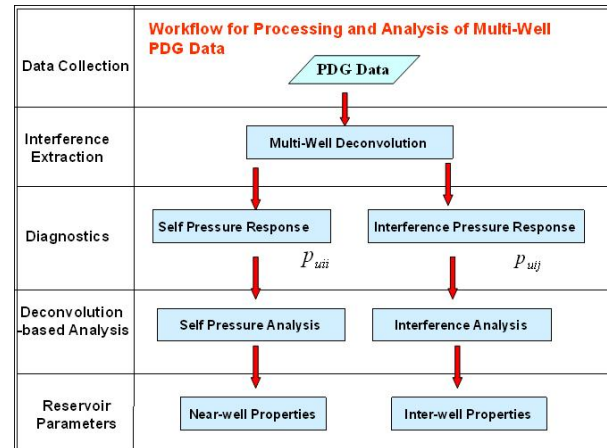
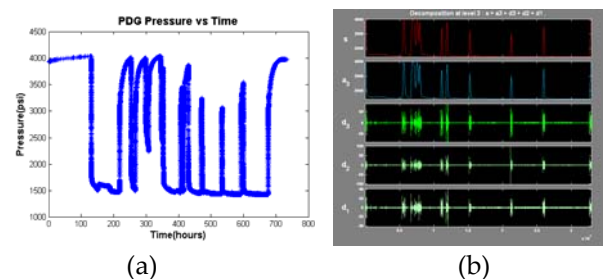


FIG. 6 DECONVOLUTION-BASED PDG DATA PROCESSING

Firstly, the multi-well deconvolution transform algorithm has been employed to extract the well interference from the total pressure response and get the decomposed well self pressure response p_{uii} and the well interference response p_{uij} . Finally deconvolution-based self pressure analysis could be used to obtain near-well properties and interference analysis of the extracted p_{uij} could be carried out to reveal inter-well properties.

Field Example

The purpose of this simple example is to illustrate the procedures of the wavelet and deconvolution approaches. Fig.7(a) displays the history of permanent down-hole gauge test in North sea field. The dataset of this example is one month data which is about 30,000 data points.



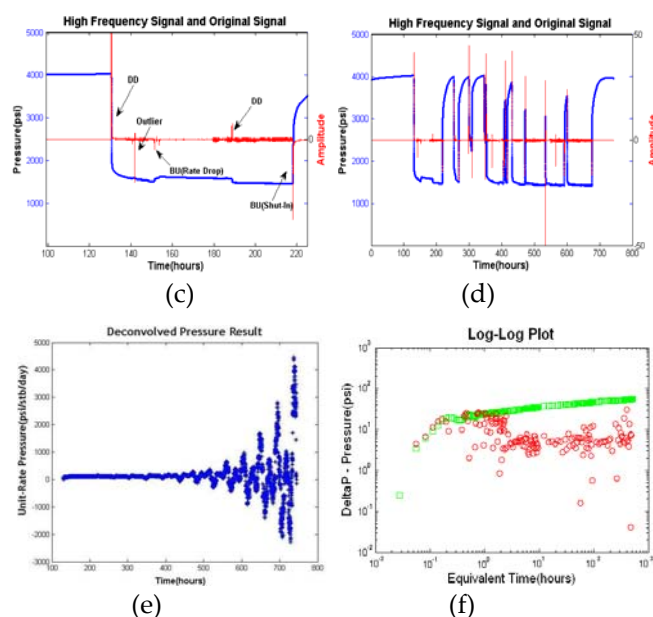


FIG.7 PROCESSING AND INTERPRETATION OF PDG DATA

As stated above, wavelet transform can decompose the original signal into different level wavelet signal in different frequency. In Fig.7(b), the red curve is the original signal. The haar wavelet, used to decompose the original into four level signals (d1, d2, d3 and a3), is found to be available to identify the event in PDG data because the signal is step change during the event happens. d1, d2, and d3 are all high frequency signal, while the a3 is low frequency signal. The three detail signal (d1, d2 and d3) reflect the high frequency part of signal. However, here we just use the highest frequency detail signal to detect event because the high frequency gives high resolutions. As shown in Fig.7(c), the blue line is the original pressure data and the red line is the highest frequency signal of original signal. Any events can cause a sharp change in the high frequency. The value of these events in the high frequency is more than zero. And this can be used to distinguish the different type events.

Fig.7(c) shows some events which can be identified based on high frequency signal with our algorithm. The principle is that the value of high frequency is positive when DD happens and the values are negative when BU happens. And both will happen when the outlier is met. But this rule is just suitable for ideal case or low frequency recorded data. However, for this case study, the algorithm need consider more condition to distinguish these 33 events i.e. all the BUs and DDs caused by the rate change, shown in Fig.7(d).

Then multi-well deconvolution algorithm is implemented on the pressure BUs and DDs without outlier. The interference pressure response is extracted

and the self pressure response is obtained simultaneously, shown in Fig.7(e). Fig.7(f) shows the deconvolved self pressure and its derivative on log-log plot. Three flow regimes are clearly identified by the derivative curve. Thereafter, traditional pressure transient analysis can be used to calculate the reservoir parameters.

Conclusions

This paper systematically introduces permanent down-hole gauge system and data. The characteristic of PDG data is long-term and large-volume, inherently noisy, full of multi-rate superposition and multi-well interference effects.

For this reason, the paper presents a systematic methodology for processing permanent down-hole gauge data, utilizing both the wavelet transform and multi-well deconvolution techniques. Wavelet transform extracts the outlier information from the PDG data, detects the pressure events and separates the BUs from the DDs. Recovery of this information early in the processing procedure is necessary and significant for the post-process results.

Multi-well deconvolution removes the effects of well rate variation and interferences from other wells operating in the reservoir and reconstructs the characteristic pressure transient response to unit-rate production of each active well in the reservoir. Deconvolved responses reflect reservoir properties and connectivity across the reservoir. Recovery of this information through integrated analysis of dynamic pressure data provides an opportunity to get more well and reservoir information.

Field example shows the power of our algorithms to process long term PDG data with the integrated methodology presented in this paper. The whole workflow provides the industry engineers a framework for reservoir monitoring and testing through permanent down-hole gauges.

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